Chemical Abundances in the Universe: Connecting First Stars to Planets
Proceedings IAU Symposium No. 265, 2009
K. Cunha, M. Spite & B. Barbuy, eds.

doi:10.1017/S1743921310000554

Thermohaline mixing in stars and the long-standing ^{3}He problem

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Abstract. Thermohaline mixing has been recently identified as the dominating process that governs the photospheric composition of low-mass bright giant stars (Charbonnel & Zahn 2007). Here we present the predictions of stellar models computed with the code STAREVOL taking into account this mechanism together with rotational mixing and atomic diffusion. We compare our theorical predictions with recent observations and discuss how the corresponding yields for ^{3}He are compatible with the observed behaviour of this light element in our Galaxy.

Keywords. hydrodynamics, instabilities, stars: abundances, evolution, rotation, Galaxy: abundances

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1. Introduction

The classical theory of stellar evolution predicts a very simple Galactic destiny to ^{3}He, dominated by a large production of this isotope by low-mass stars (Iben 1967; Rood 1972; Rood *et al.* 1976; Dearborn *et al.* 1996; Weiss *et al.* 1996). As a consequence, one expects a large increase of ^{3}He with time in the Galaxy with respect to its primordial abundance (e.g., Tosi 1996). However, the ^{3}He content of Galactic HII regions (Balser *et al.* 1994, 1999a; Bania *et al.* 1997, 2002) is similar to that of the Sun and the solar system (Geiss & Reeves 1972; Geiss 1993, Mahaffy *et al.* 1998), and very close to the BBN value (Coc *et al.* 2004; Cyburt 2004; Serpico *et al.* 2004). This is the so-called "^{3}He problem" that could be resolved if only $\sim$10 % or less of the low-mass stars were releasing ^{3}He as predicted by classical stellar theory (Tosi 1998, 2000; Palla *et al.* 2000; Romano *et al.* 2003).

In 2007, Charbonnel & Zahn showed that thermohaline mixing drastically reduces the ^{3}He production in low-mass, low-metallicity stars. Simultaneously, this mechanism changes the surface carbon isotopic ratio as well as the abundances of lithium, carbon and nitrogen.

2. Stellar models including thermohaline convection, rotation-induced mixing, and atomic diffusion

Here we present the predictions of new stellar models computed with the code STAREVOL for solar metallicity. Computations include the transport of chemical species in the radiative regions due to thermohaline instability, rotational mixing, and atomic diffusion. For thermohaline transport we use the diffusion coefficient advocated by Charbonnel & Zahn (2007) that is supported by laboratory experiments (Krishnamurti 2003). The evolution of the internal angular momentum profile and the resulting transport of

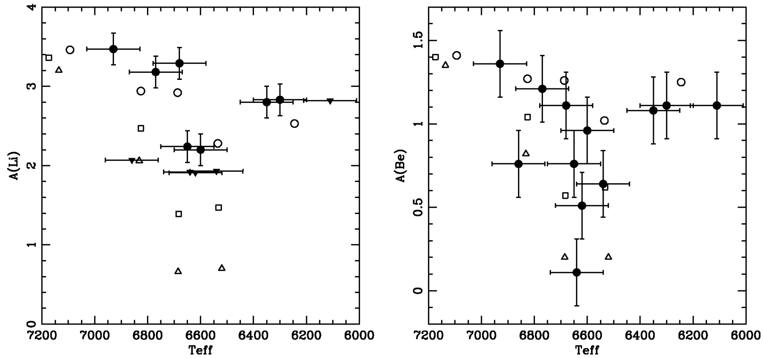

Figure 1. Li and Be abundances in IC 4651 main sequence and turnoff stars (black points and triangles for actual determinations and upper limits respectively). Open circles, squares, and triangles show model predictions for initial rotation velocities of 50, 80, and 110 km s^{-1} respectively. On the cool side of the Li and Be dip the model with Teff∼6250 K is from Talon & Charbonnel (2005) and takes into account additional transport of angular momentum by internal gravity waves. Figures from Smiljanic *et al.* (2009)

chemicals are accounted for with the complete formalism developed by Zahn(1992) and Maeder & Zahn (1998) that takes into account advection by meridional circulation and diffusion by shear turbulence (see Palacios *et al.* 2003, 2006 and Decressin *et al.* 2009 for a description of the implementation in STAREVOL). Typical initial (i.e., ZAMS) surface rotation velocities are chosen for all the models depending on the stellar mass. We assume magnetic braking on the early main sequence for the stars with Teff on the ZAMS lower than ∼ 6900 K that have relatively thick convective envelopes. The adopted braking law follows the description of Kawaler (1988). Rotational velocity further decreases when the stars evolve on the subgiant branch due to radius expansion. Atomic diffusion is included in the form of gravitational settling as well as that related to thermal gradients, using the formulation of Paquette *et al.* (1986).

3. Model predictions for the surface abundances

The model predictions for the evolution of the surface abundances of various species have been validated all along the evolutionary sequence. They reproduce for example very well the surface abundances of Li and Be in main sequence stars as shown in Fig. 1 in the case of data for the open cluster IC 4651, as well as in subgiant and giant stars (see Smiljanic *et al.* 2009 for more details).

Predictions for the evolution of the surface carbon isotopic ratio are shown in Fig. 2 for models of 1.25 and 2 $M_\odot$ stars, and compared with observations in the open cluster M67 (turnoff mass ∼1.2 $M_\odot$). We note that rotation-induced mixing on the main sequence slightly lowers the post-dredge-up $^{12}C/^{13}C$ value compared to the classical case. At the luminosity of the bump ($\log(L/L_\odot)\sim 2$ for the 1.25 $M_\odot$ star), thermohaline mixing leads to further decrease of the carbon isotopic ratio, in excellent agreement with M67 data (see Charbonnel & Zahn 2007 for comparisons with low-metallicity stars). In the case of the 2 $M_\odot$ star, thermohaline mixing becomes efficient at the bump in the luminosity function only when rotation in earlier phases is accounted for.

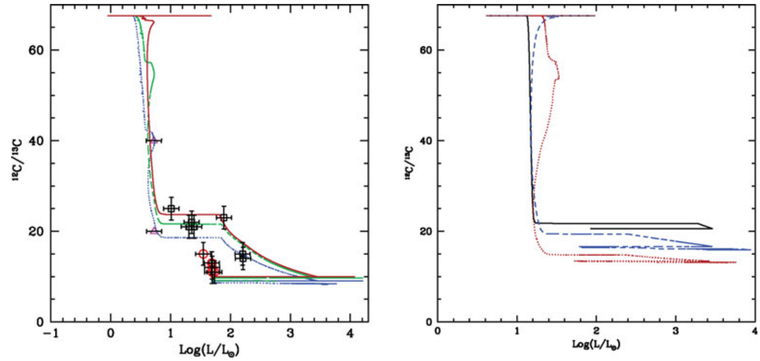

Figure 2. Evolution of the surface ^{12}C/^{13}C value as a function of stellar luminosity for the 1.25 and 2 M$_\odot$ models (left and right respectively). Different tracks correspond to different initial rotation velocities (50, 80, and 110 km.s^{-1} for the 1.25 M$_\odot$, and 0, 110, and 250 km.s^{-1} for the 2 M$_\odot$). Observations for M67 stars by Gilroy & Brown (1991) are also shown (triangle, squares, and circles for subgiant, RGB, and clump stars respectively; turnoff mass of M67 ∼1.2 M$_\odot$). Figures from Lagarde & Charbonnel (in preparation)

4. Model predictions for ^{3}He

On the main sequence, a ^{3}He peak builds up due to pp-reactions inside the low-mass stars, and is engulfed in the stellar envelope during the first dredge-up. As a consequence the surface abundance of ^{3}He strongly increases on the lower RGB as can be seen in Fig. 3 for stars of different masses. Its value reaches a maximum when the whole peak is engulfed. After the first dredge-up, the temperature at the base of the convective envelope is too low for ^{3}He to be nuclearly processed. As a result in canonical models ^{3}He stays constant at the surface until the ejection of the planetary nebula and its final value is strongly increased with respect to the initial one (this is the value before thermohaline mixing sets in at the bump).

In the present models however, thermohaline mixing sets in at the bump, and brings ^{3}He from the convective envelope down to the hydrogen-burning shell. This leads to a rapid decrease of the surface abundance of this element as can be seen in Fig. 3, and as already shown by Charbonnel & Zahn (2007) for low-metallicity stars. This confirms the early suggestion by Rood *et al.* (1984) that the variations of the carbon isotopic ratio and of ^{3}He are strongly connected (see also Charbonnel 1995 and Eggleton *et al.* 2006). It is important to note that in the models presented here ^{3}He decreases by a large factor in the ejected material with respect to the canonical evolution predictions but that low-mass stars remain net ^{3}He producers (while far much less efficient than in the canonical case).

Computations for a larger grid in stellar masses and metallicities are now being performed in order to quantify the actual contribution of low-mass stars to Galactic ^{3}He in the framework proposed here. We are confident that the corresponding ^{3}He yields will help reconciling the primordial nucleosynthesis with measurements of ^{3}He/H in Galactic HII regions (Charbonnel 2002).

Acknowledgements

We acknowledge financial support from IAU, from the French "Programme National de Physique Stellaire" of CNRS/INSU, and from the Swiss National Science Foundation.

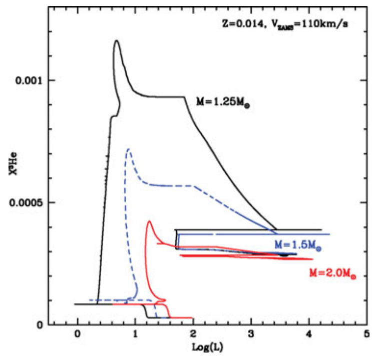

Figure 3. Evolution of the surface abundance of ^{3}He (in mass fraction) for solar metallicity stars of various initial masses. Figure from Lagarde & Charbonnel (in preparation)

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